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(54) Bi-stable expandable device and method for expanding such a device

(57) An expandable device comprising a plurality of expandable cells (23). The cells may be bistable cells or other types of cells that are expanded from a contracted position towards an expanded position. Additionally, the cells may be combined with locking mechanisms to hold the structure in an expanded position.

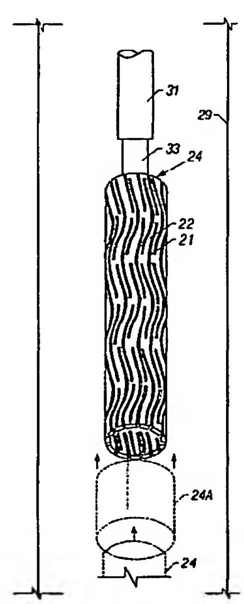

FIG. 4C

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Description

[0001] This invention relates generally to expandable devices, and particularly to devices formed from one or more expandable cells that facilitate transition of the device from a contracted state to an expanded state.

[0002] In a variety of applications and environments, it would be beneficial to have a device able to transition from a contracted state to an expanded state. Such devices can comprise planar members, tubular members, rectangular members and a variety of other configurations. Exemplary applications include medical applications in which expandable devices, such as stents, are deployed at a desired location and then expanded. Another exemplary application comprises the use of expandables in the retrieval of various fluids, e.g. oil, from subterranean locations.

[0003] For example, fluids such as oil, natural gas and water are obtained from subterranean geologic formations (a "reservoir") by drilling a well that penetrates the fluid-bearing formation. Once a wellbore has been drilled to a certain depth, the borehole wall typically is supported to prevent collapse. During the drilling and use of a wellbore, various tubular members, such as liners. casings, sandscreens, etc. are deployed within the wellbore.

[0004] Various methods have been developed for radially expanding tubulars by, for instance, pulling an expansion mandrel through the tubular to plastically deform the tubular in a radially outward direction. Such an approach, however, requires a large amount of force to achieve the desired expansion.

[0005] The medical industry, oil industry and a variety of other industries utilize certain types of expandables or would benefit from the use of expandables in numerous applications. However, there are very few existing devices that are readily expandable at a desired location. Of the devices that do exist, substantial forces are required to create the expansion. Also, substantial plastic deformation often occurs which can limit the selection of available materials for a given expandable device. The present invention is directed to overcoming, or at least reducing, the effects of one or more of the problems set forth above.

[0006] The present invention relates generally to expandable devices that may be used, for example, in subterranean environments. In one embodiment of the invention, the expandable device comprises one or more expandable cells that facilitate expansion of the device. By way of example, a tubular may be formed with a plurality of expandable cells that facilitate radial expansion of the device from a collapsed or contracted state to an expanded state. A variety of cell types and cell designs may be utilized depending on the application and desired parameters of the expandable device.

[0007] The invention will hereafter be described with reference to the accompanying drawings, wherein like reference numerals denote like elements, and:

Figures 1A and 1B are illustrations of the forces imposed to make a bistable structure;

Figure 2A and 2B show force-deflection curves of two bistable structures;

Figures 3A - 3F illustrate expanded and collapsed states of three bistable cells with various thickness ratios;

Figures 4A and 4B illustrate a bistable expandable tubular in its expanded and collapsed states;

Figures 4C and 4D illustrate a bistable expandable tubular in collapsed and expanded states within a wellbore;

Figures 5A and 5B illustrate an expandable packer type of deployment device;

Figures 6A and 6B illustrate a mechanical packer type of deployment device;

Figures 7A - 7D illustrate an expandable swage type of deployment device;

Figures 8A - 8D illustrate a piston type of deployment device;

Figures 9A and 9B illustrate a plug type of deployment device;

Figures 10A and 10B illustrate a ball type of deployment device;

Figure 11 is a schematic of a wellbore utilizing an expandable bistable tubular;

Figure 12 illustrates a motor driven radial roller deployment device;

Figure 13 illustrates a hydraulically driven radial roller deployment device;

Figure 14 is a cross sectional view of one embodiment of the packer of the present invention;

Figure 15 is a cross sectional view of another embodiment of the packer of the present invention;

Figure 16 is a side elevation view of an embodiment of the present invention in a contracted state;

Figure 17 is a side elevation view of an embodiment of the present invention in an expanded state;

Figures 18A-C are schematic views of an alternative embodiment of the present invention;

of applications in other environments and industries.

[0010] As described below, exemplary expandable devices may or may not comprise bistable cells. Whether bistable or not, the expandable cells facilitate expansion of a given device between a contracted state and an expanded state for a variety of operations or procedures. The selection of a particular type of expandable cell depends on a variety of factors including environment, degree of expansion, materials available, etc.

[0011] Bistable devices used in the present invention can take advantage of a principle illustrated in Figures 1A and 1B. Figure 1A shows a rod 10 fixed at each end to rigid supports 12. If the rod 10 is subjected to an axial force it begins to deform as shown in Figure 1B. As the axial force is increased rod 10 ultimately reaches its Euler buckling limit and deflects to one of the two stable positions shown as 14 and 15. If the buckled rod is now clamped in the buckled position, a force at right angles to the long axis can cause the rod to move to either of the stable positions but to no other position. When the rod is subjected to a lateral force it must move through an angle β before deflecting to its new stable position.

[0012] Bistable systems are characterized by a force deflection curve such as those shown in Figures 2A and 2B. The externally applied force 16 causes the rod 10 of Fig. IB to move in the direction X and reaches a maximum 18 at the onset of shifting from one stable configuration to the other. Further deflection requires less force because the system now has a negative spring rate and when the force becomes zero the deflection to the second stable position is spontaneous.

[0013] The force deflection curve for this example is symmetrical and is illustrated in Figure 2A. By introducing either a precurvature to the rod or an asymmetric cross section the force deflection curve can be made asymmetric as shown in Figure 2B. In this system the force 19 required to cause the rod to assume one stable position is greater than the force 20 required to cause the reverse deflection. The force 20 must be greater than zero for the system to have bistable characteristics.

[0014] Bistable structures, sometimes referred to as toggle devices, have been used in industry for such devices as flexible discs, over center clamps, holddown devices and quick release systems for tension cables (such as in sailboat rigging backstays).

[0015] Instead of using the rigid supports as shown in Figures 1A and 1B, a cell can be constructed where the restraint is provided by curved struts connected at each end as shown in Figures 3A - 3F. If both struts 21 and 22 have the same thickness as shown in Figures 3A and 3B, the force deflection curve is linear and the cell lengthens when compressed from its open position Figure 3B to its closed position Figure 3A. If the cell struts have different thicknesses, as shown in Figures 3C - 3F, the cell has the force deflection characteristics shown in Figure 2B, and does not change in length when it moves between its two stable positions. An expandable bistable tubular can thus be designed so that as the radial dimension expands, the axial length remains constant. In one example, if the thickness ratio is over approximately 2:1, the heavier strut resists longitudinal changes. By changing the ratio of thick-to-thin strut dimensions, the opening and closing forces can be changed. For example, Figures 3C and 3D illustrated a thickness ratio of approximately 3:1, and Figures 3E and 3F illustrate a thickness ratio of approximately 6:1.

[0016] An expandable bore bistable tubular, such as casing, a tube, a patch, or pipe, can be constructed with a series of circumferential bistable connected cells 23 as shown in Figures 4A and 4B, where each thin strut 21 is connected to a thick strut 22. The longitudinal flexibility of such a tubular can be modified by changing the length of the cells and by connecting each row of cells with a compliant link. Further, the force deflection characteristics and the longitudinal flexibility can also be altered by the design of the cell shape. Figure 4A illustrates an expandable bistable tubular 24 in its expanded configuration while Figure 4B illustrates the expandable bistable tubular 24 in its contracted or collapsed configuration. Within this application the term "collapsed" is used to identify the configuration of the bistable element or device in the stable state with the smallest diameter, it is not meant to imply that the element or device is damaged in any way. In the collapsed state, bistable tubular 24 is readily introduced into a wellbore 29, as illustrated in Figure 4C. Upon placement of the bistable tubular 24 at a desired wellbore location, it is expanded, as illustrated in Figure 4D.

[0017] The geometry of the bistable cells is such that the tubular cross-section can be expanded in the radial direction to increase the overall diameter of the tubular. As the tubular expands radially, the bistable cells deform elastically until a specific geometry is reached. At this point the bistable cells move, e.g. snap, to a final expanded geometry. With some materials and/or bistable cell designs, enough energy can be released in the elastic deformation of the cell (as each bistable cell snaps past the specific geometry) that the expanding cells are able to initiate the expansion of adjoining bistable cells past the critical bistable cell geometry. Depending on the deflection curves, a portion or even an entire length of bistable expandable tubular can be expanded from a single point.

[0018] In like manner if radial compressive forces are exerted on an expanded bistable tubular, it contracts radially and the bistable cells deform elastically until a critical geometry is reached. At this point the bistable cells snap to a final collapsed structure. In this way the expansion of the bistable tubular is reversible and repeatable. Therefore the bistable tubular can be a reusable tool that is selectively changed between the expanded state as shown in Figure 4A and the collapsed state as shown in Figure 4B.

[0019] In the collapsed state, as in Figure 4B, the bistable expandable tubular is easily inserted into the wellbore and placed into position. A deployment device is

- 7D and comprises a series of fingers 28 that are arranged radially around a conical mandrel 30. Figures 7A and 7C show side and top views respectively. When the mandrel 30 is pushed or pulled through the fingers 28 they expand radially outwards, as illustrated in Figures 7B and 7D. An expandable swage is used in the same manner as a mechanical packer element to deploy a bistable expandable tubular and connector.

[0029] A piston type apparatus is shown in Figures 8A - 8D and comprises a series of pistons 32 facing radially outwardly and used as a mechanism to expand the bistable expandable tubulars and connectors. When energized, the pistons 32 apply a radially directed force to deploy the bistable expandable tubular assembly as per the inflatable packer element. Figures 8A and 8C illustrate the pistons retracted while Figures 8B and 8D show the pistons extended. The piston type apparatus can be actuated hydraulically, mechanically or electrically.

[0030] A plug type actuator is illustrated in Figures 9A and 9B and comprises a plug 34 that is pushed or pulled through the bistable expandable tubulars 24 or connectors as shown in Figure 9A. The plug is sized to expand the bistable cells past their critical point where they will snap to a final expanded diameter as shown in Figure 9B.

[0031] A ball type actuator is shown in Figures 10A and 10B and operates when an oversized ball 36 is pumped through the middle of the bistable expandable tubulars 24 and connectors. To prevent fluid losses through the cell slots, an expandable elastomer based liner 38 is run inside the bistable expandable tubular system. The liner 38 acts as a seal and allows the ball 36 to be hydraulically pumped through the bistable tubular 24 and connectors. The effect of pumping the ball 36 through the bistable expandable tubulars 24 and connectors is to expand the cell geometry beyond the critical bistable point, allowing full expansion to take place as shown in Figure 10B. Once the bistable expandable tubulars and connectors are expanded, the elastomer sleeve 38 and ball 36 are withdrawn.

[0032] Radial roller type actuators also can be used to expand the bistable tubular sections. Figure 12 illustrates a motor driven expandable radial roller tool. The tool comprises one or more sets of arms 58 that are expanded to a set diameter by means of a mechanism and pivot. On the end of each set of arms is a roller 60. Centralizers 62 can be attached to the tool to locate it correctly inside the wellbore and the bistable tubular 24. A motor 64 provides the force to rotate the whole assembly, thus turning the roller(s) circumferentially inside the wellbore. The axis of the roller(s) is such as to allow the roller(s) to rotate freely when brought into contact with the inner surface of the tubular. Each roller can be conically-shaped in section to increase the contact area of roller surface to the inner wall of the tubular. The rollers are initially retracted and the tool is run inside the collapsed bistable tubular. The tool is then rotated by the motor 64, and rollers 60 are moved outwardly to contact the inner surface of the bistable tubular. Once in contact with the tubular, the rollers are pivoted outwardly a greater distance to apply an outwardly radial force to the bistable tubular. The outward movement of the rollers can be accomplished via centrifugal force or an appropriate actuator mechanism coupled between the motor 64 and the rollers 60.

[0033] The final pivot position is adjusted to a point where the bistable tubular can be expanded to the final diameter. The tool is then longitudinally moved through the collapsed bistable tubular, while the motor continues to rotate the pivot arms and rollers. The rollers follow a shallow helical path 66 inside the bistable tubular, expanding the bistable cells in their path. Once the bistable tubular is deployed, the tool rotation is stopped and the roller retracted. The tool is then withdrawn from the bistable tubular by a conveyance device 68 that also can be used to insert the tool.

[0034] Figure 13 illustrates a hydraulically driven radial roller deployment device. The tool comprises one or more rollers 60 that are brought into contact with the inner surface of the bistable tubular by means of a hydraulic piston 70. The outward radial force applied by the rollers can be increased to a point where the bistable tubular expands to its final diameter. Centralizers 62 can be attached to the tool to locate it correctly inside the wellbore and bistable tubular 24. The rollers 60 are initially retracted and the tool is run into the collapsed bistable tubular 24. The rollers 60 are then deployed and push against the inside wall of the bistable tubular 24 to expand a portion of the tubular to its final diameter. The entire tool is then pushed or pulled longitudinally through the bistable tubular 24 expanding the entire length of bistable cells 23. Once the bistable tubular 24 is deployed in its expanded state, the rollers 60 are retracted and the tool is withdrawn from the wellbore by the conveyance device 68 used to insert it. By altering the axis of the rollers 60, the tool can be rotated via a motor as it travels longitudinally through the bistable tubular 24.

[0035] Power to operate the deployment device can be drawn from one or a combination of sources such as: electrical power supplied either from the surface or stored in a battery arrangement along with the deployment device, hydraulic power provided by surface or downhole pumps, turbines or a fluid accumulator, and mechanical power supplied through an appropriate linkage actuated by movement applied at the surface or stored downhole such as in a spring mechanism.

[0036] The bistable expandable tubular system is designed so the internal diameter of the deployed tubular is expanded to maintain a maximum cross-sectional area along the expandable tubular. This feature enables mono-bore wells to be constructed and facilitates elimination of problems associated with traditional wellbore casing systems where the casing outside diameter must be stepped down many times, restricting access, in long wellbores.

[0037] The bistable expandable tubular system can

as a tubing) has a portion (marked as the packer 80) that is cut to form the bistable cells. The packer portion 80 has a seal 84 thereon as previously described. In Figure 16, a portion of the seal material 84 is illustrated as removed to reveal the bistable cells 83 in the underlying tubular 82. In Figure 17, the packer portion 80 is illustrated in its expanded state. It should be noted that in typical applications the well conduit 90 which does not have bistable cells formed therein, does not expand. Thus, one embodiment for attaching the well conduit to the packer 80 is to form the packer 80 as an integral part of the well conduit 90 (note that a welded connection resembles this embodiment and is an alternative method of forming the present invention). Other methods include conventional methods of non-integral connection.

[0048] In alternative embodiments, the well conduit has a plurality of bistable cell packers 80 formed thereon. In yet another alternative embodiment, a portion or portions 91 of the well conduit in addition to the packer portions 80 are formed of bistable cells so that these other portions also undergo expansion (see Figure 17). The other portions may or may not have a material applied thereto. For example, the other portion may have a screen or filter material applied thereto to provide a well sand screen.

[0049] Referring to Figures 18A-C, an alternative design of the present invention is illustrated in a schematic, partial cross-sectional view. The expandable packer is shown in the retracted and expanded states, respectively, and in partial side elevational view (Figure 18C). The packer shown includes a base tubular 82 formed of thin struts 21 and thick struts 22 forming bistable cells 23/83 as previously described. Slats 92 are attached to the tubing 82 at one edge and extend generally longitudinally in the embodiment shown (see Figure 18C). Specifically, each slat 92 is attached to the tubing 82 at the thick struts 22, and the width of the slats is such that they overlap at least the adjacent slat when the tubing 82 is in the expanded state. Although illustrated as having a slat attached to each of the thick struts, the packer may have a slat attached to alternate thick struts 22 or in other configurations. Furthermore, the slats may extend in a direction other than the longitudinal direction. The slats 92 slide over one another during expansion so that the outside of the tubing 82 is covered by the overlapping slats 92.

[0050] A seal 84 may be attached to the slats 92 to provide the seal for the packer. Although shown in the figures as folded, the seal 84, may have other characteristics that facilitate its ability to expand with the slats 92 and tubular 82. Also, the seal 84 may have other characteristics previously mentioned (e.g., resin, internal seal, etc).

[0051] It should be noted that although described as a packer, the present invention may be used to provide isolation over a long length as opposed to a traditional packer or downhole tool which generally seals only a relatively short longitudinal distance. Thus, the present invention may be used in a manner similar to a casing to provide isolation for an extended length.

[0052] In Figure 19, a perspective view of packer 80 (or isolation device) having a plurality of slats 92 attached thereto is illustrated in an overlapping arrangement as previously described. The tubing 82 includes end extensions 94 that extend longitudinally from the endmost cells. The slats 92 may be attached to the end extensions 94, to certain portions of the thick struts 22 and/or to certain thick struts 22. In one embodiment, for example, the struts 92 are attached to the thick struts which are longitudinally aligned with the end extensions 94. Although generally shown as attached at an edge of the slats 92, the slats also may attach to the tubing 82 at a position intermediate the edges.

[0053] In Figure 20, an expandable tubing (or conduit) 90 is illustrated positioned in a well 100. The conduit 90 includes a plurality of spaced packers 80 or expandable sealing devices. The expandable packers 80 engage the wellbore wall preventing annular flow thereby. Therefore, any microannulus formed between the expandable tubing 90 and the well 100 (which may include a casing) is sealed in the longitudinal direction to restrict or prevent unwanted flow thereby. The conduit 90 may include one or more such packers 80, as desired, to control the flow. Further, the packers 80 may be spaced at regular intervals or at some other predetermined spacing to control the flow in the annulus as needed.

[0054] In one example, illustrated schematically in Figure 21, the individual joints of tubing 90 are interconnected by a packer 80 to compartmentalize each joint of conduit from the adjacent joint(s). The packer 80 can be a separate connector as shown in Figure 21 or it can be formed as part of the joint. Accordingly, the packer 80 can be positioned at an end of the joint 90, in the middle of the joint 90, or at any other location along its length. In one embodiment both conduit 90 and packers 80, of Figures 20 and 21, are formed of bistable cells.

[0055] Referring generally to Figures 22A-B, an alternative embodiment of the present invention is disclosed. The device shown in these figures may be used as a packer, hanger, casing patch, or other device requiring expansion and is generally referred to herein in reference to these figures as an expandable tubular 120 for ease of description. The expandable tubular 120 comprises a series of cells 122 formed therein, such as by laser cutting, jet cutting, water jet cutting or other manufacturing methods. The cells 122 are oriented such that a number of longitudinal struts 24 are formed on the expandable tubular 120. Thus, as shown in the figures, the longitudinal struts 124 lie between longitudinal lengths of cells 122 with the cells 122 having relatively thinner struts 126 extending between adjacent longitudinal struts 124. As shown in the figures, as the adjacent longitudinal struts 124 are moved longitudinally relative to one another (e.g. in opposite directions), the cells 122 open to expand the structure radially. Not all of the longitudinal struts 124 must move; alternate longitudinal

each cell 150 have outlying ends 156 pivotably coupled to upper attachment regions 160 of the lower thick strut 152. The opposite ends of each pair of thin struts 154 are pivotably coupled to a lower attachment region 162 of the next upwardly adjacent thick strut 152. It should be noted that positional terms such as upper and lower or merely used to facilitate explanation of the location of various features relative to the figures provided and should not be construed as limiting.

[0064] In another embodiment illustrated in Figures 27A and 27B, a plurality of expandable cells, labeled with reference numeral 164, each comprise a thick strut 166 and one or more thin struts 168. Each thick strut 166 is generally arcuate and connected to a corresponding thin strut 168 at a fixed connection region 170 disposed at a generally central location along the outer or convex portion of the arcuate thick strut. The outer ends of each thin strut 168 are pivotably coupled to the next adjacent thick strut 166 via a pivot connection 172 that may comprise a ball and socket.

[0065] As the plurality of cells are moved from the contracted state illustrated in Figure 27A to the expanded state illustrated in Figure 27B, thin struts 168 flex or deform as their outer ends pivot at each pivot connection 172. As with many of the other cells described herein, when the thin struts 168 move past their point of greatest flexure, the stored spring energy tends to force the cells 164 to their stable expanded state illustrated in Figure 27B. Thus, as with the bistable cells illustrated in Figures 26A and 26B, cells 164 move between a stable contracted state and a stable expanded state.

[0066] Another expandable cell embodiment is illustrated in Figures 28A and 28B. In this embodiment, each expandable cell 174 is formed of a thick strut 176 and a thin strut 178. Each thin strut 178 has a pair of ends 180 that are pivotably coupled to a thick strut. For example, a given thick strut may comprise a pair of sockets 182 to pivotably receive pin or ball shaped ends 180. Additionally, thin strut 178 is fixedly coupled to adjacent thick struts 176 in an alternating pattern. For example, each cell in the illustrated embodiment comprises three fixed couplings 184 that alternate between adjacent thick struts 176. With this design, the expandable cells 174 again are movable between a stable contracted state as illustrated in Figure 28A and a stable expanded state as illustrated in Figure 28B.

[0067] With reference to Figures 29A and 29B, another expandable cell design is illustrated. In this embodiment, each of a plurality of expandable cells 186 comprises a thick strut 188 and at least a pair of stacked thin struts 190, 192, respectively. Thin struts 190, 192 are generally disposed in a stacked orientation and connected by a linking member 194. Thin strut 192 comprises a pair of ends 196 affixed to a corresponding thick strut 188. An intermediate connection region 198 of thin strut 192 is affixed to the next adjacent thick strut 188, as best illustrated in Figure 29B. Thin strut 190, on the other hand, has unattached ends 200. Ends 200 are captured in an abutting engagement with a notched region 202 formed in the same thick strut 188 to which ends 196 are affixed. As the plurality of expandable cells 186 are moved from the contracted state illustrated in Figure 29A to the expanded state illustrated in Figure 29B, each pair of thin struts 190 and 192 deforms to a deflection point where stored energy in the thin struts is maximized. As the thin struts are moved past this deflection point, the stored energy is released to facilitate expansion of the cells to their expanded state.

[0068] Of course, with any of these types of bistable cells, the degree of expansion may be limited by an external barrier. For example, if the bistable cells are used to form a tubular, the tubular may be expanded against a wellbore wall that prevents the cells from moving to their fully expanded condition. Typically, the size of the tubular is selected to permit expansion of the cells at least past the point of maximum deformation. Thus, depending on the material used, the cells may actually cooperate to apply an outwardly directed radial force against the wellbore wall.

[0069] Referring generally to Figures 30A and 30B, another expandable cell design is illustrated. Each expandable cell 204 comprises a pair of arcuate thin struts 206 pivotably coupled to a corresponding thick strut 208 at a generally centralized extended region 210 via pivot ends 212. Generally opposite pivot ends 212, thin struts 206 comprise outer pivot ends 214 that are pivotably coupled to the next adjacent thick strut 208. Pivot ends 212 and 214 can be formed in a variety of configurations, such as ball joints, pin joints, etc. Removal of each thin strut 206 is prevented by appropriate ligaments 216 and 218 disposed at pivot ends 212 and 214, respectively. The ligaments 216 and 218 are coupled between the thin strut 206 and the corresponding thick struts 208.

[0070] In Figures 31A-31C, a different type of expandable cell 220 is illustrated. In this embodiment, a thick strut 222 is coupled to one or more thin struts 224 by one or more spring elements 226. In the particular embodiment illustrated, two spring elements 226 are formed generally in the shape of a horn, with the base of each horn connected to thick strut 222 and the tip of each horn coupled to the adjacent thin strut 224. In this embodiment, a thin strut 224 is connected to each spring element 226 by a flexible hinge 228. The two thin struts 224 are coupled to each other through a center beam 230 and a pair of flexible hinges 232.

[0071] As cells 220 are expanded from a contracted state, illustrated in Figure 31A, to an expanded state, illustrated in Figure 31C, spring elements 226 flex outwardly and store spring energy. With this design, thin struts 224 typically do not undergo substantial deformation during movement from the contracted state to the expanded state. Rather, spring elements 226 are elastically deformed as they are forced outwardly during movement of center beam 230 from the contracted state to the expanded state. When spring elements 226 are flexed outwardly, they store spring energy at least to the

riety of expandable cell and locking mechanism combinations are illustrated. With specific reference to Figures 38A and 38B, one embodiment of an expandable cell 302 comprises thick struts 304 that are coupled together by thin struts 306 via spring members 308. Each thick strut 304 comprises one or more, e.g. two, ratchet fingers 310 that slide along a corresponding ratchet surface 312 formed on expanded regions of the thin struts 306 (see Figure 38B).

[0082] Ratchet surface 312 may incorporate ratchet teeth to engage the end of the corresponding ratchet finger 310. As the expandable cell 302 is transitioned from its contracted state, as illustrated in Figure 38A, to an expanded state, as illustrated in Figure 38B, ratchet fingers 310 are flexed away from a support surface 314 while sliding along corresponding ratchet surfaces 312. The ends of the ratchet fingers 310 do not allow sliding motion of corresponding ratchet surfaces 312 back towards the contracted state. Furthermore, support surfaces 314 may be relied on to limit any flexing of fingers 310 back towards the contracted position. Thus, when the expandable cell in its expanded state, each of the ratchet fingers 310 acts against a corresponding ratchet surface 312 to support the cell against collapse.

[0083] Another embodiment of the system is illustrated in Figure 39 and utilizes fingers in the form of ratchet pawls 316. In this embodiment, each ratchet pawl is formed in an appropriate thick strut 304 by creating an open area 318 configured to receive a corresponding portion 320 of thin strut 306 when in the contracted position. Each ratchet pawl 316 may comprise a plurality of teeth 322 positioned to engage corresponding teeth 324 extending from portion 320. Additionally, a relief cut 326 may be formed along ratchet pawl 316 generally opposite open area 318. Relief cut 326 allows ratchet pawl 316 to flex as teeth 322 are dragged past teeth 324 during transition of the cell from a contracted state to an expanded state. Teeth 322 and 324 are designed to prevent closure of the cell once expansion begins. Thus, the ratchet pawl 316 effectively ratchets along portion 320 holding the cell at each additional degree of expansion. As an alternative to teeth, the ratchet pawl 316 and cooperating portion 320 may utilize other types of interfering features to prevent contraction of the cell.

[0084] The locking mechanisms also may be used in cooperation with expandable cells that are not necessarily bistable cells. For example, in Figure 40A an expandable cell 330 comprises a thin strut 332 disposed in an expandable "wishbone" type configuration between the thick struts 334 to which it is connected. A locking mechanism 336 cooperates with one or more of the expandable thin struts 332 to hold the expandable cells 330, at an expanded position. As illustrated in Figure 40B, a locking mechanism 336 may be combined with each expandable cell 330, or there may be multiple expandable cells for each locking mechanism 336.

[0085] In this embodiment, locking mechanism 336 comprises a post 338 having external teeth 340. Post 338 is slidably received within an opening 342 defined by one or more flexible fingers 344 having engagement tips 346 that engage teeth 340. Fingers 344 flex outwardly to allow teeth 340 to slide past engagement tips 346 as the cell is expanded, but engagement tips 346 prevent post 338 from moving in a direction towards the contracted state. Thus, once expandable cell 330 is expanded, locking mechanism 336 prevents contraction of the cell.

[0086] A similar design is illustrated in Figures 41A and 41B. This design combines the expandable cell described with reference to Figure 40A and a locking mechanism of the type described in Figures 36A-36D. Thus, as the plurality of expandable cells 330 are moved from the contracted state illustrated in Figure 41A to the expanded state illustrated in Figure 41 B, the wishbone style thin strut is expanded. Simultaneously, prongs 276 are pulled from their corresponding opening 280 to a position that prevents reentry of fork 274 into opening 280. The locking mechanism may be designed such that prongs 276 are withdrawn from and blocked from reentering opening 280. Alternatively, prongs 276 may be designed for interference with corresponding teeth or other interfering features 350 disposed along the outer limit of each opening 280 to prevent return movement of prongs 276 into opening 280.

[0087] It also should be noted that expandable devices, such as expandable tubulars, can be formed with a variety of cells and locking mechanisms having differing configurations, such as changes in size or type, as illustrated schematically in Figure 42. For example, by stacking cells of different length or eccentric offset in a sheet or tube, it is possible to design an opening bias into the structure. The expandable device may be designed to allow certain rows of cells to open prior to other rows of cells or for the cells to open in a predetermined pattern or at a predetermined rate. In Figure 42, for example, an expandable device 352 comprises rows of expandable cells 354. However, different rows 354 have cells of differing lengths, e.g. cells 356, 358 and 360. This allows certain rows of cells to open prior to adjoining rows of cells, because, at least with certain cell designs, the length of the cell affects the force required to expand the cell. Incorporating different rows of cells into an expandable device allows the user to know the rate of expansion for a given deployment force and facilitates the design of devices having cells which open in a predetermined sequence. Additionally, the use of different types of cells can improve compliance of the expandable device when the deployment force is not uniform along the length of the device.

[0088] It will be understood that the foregoing description is of exemplary embodiments of this invention, and that the invention is not limited to the specific forms shown. For example, the expandable cells can be combined into a variety of tubulars and other expandable structures; the size and shape of the expandable cells and locking mechanisms can be adjusted; the types of

that are expandable from a closed position to an open position, each cell having a thin strut coupled to a thick strut by a ligament.

23. The expandable device as recited in claim 21, wherein the thin strut and the thick strut of each cell are pivotably coupled by a pin joint.

24. The expandable device as recited in claim 21, wherein the thin strut and the thick strut of each cell are pivotably coupled by a ball and socket joint.

25. The expandable device as recited in claim 21, wherein the thin strut is coupled between a fixed end and a pivotable end.

26. A method of expanding a device, comprising:

creating a plurality of bistable cells in a wall of the device by coupling thin struts to corresponding thick struts through hinge joints; and

applying an expansion force to the wall in a direction that transitions the plurality of bistable cells from a contracted state to an expanded state.

27. The method as recited in claim 26, further comprising forming a plurality of locking mechanisms in the wall.

28. The method as recited in claim 26, wherein creating comprises coupling each thin strut to a corresponding thick strut through a pivotable hinge joint.

29. The method as recited in claim 26, wherein creating comprises coupling each thin strut to a corresponding thick strut through a flexible hinge joint.

30. The method as recited in claim 26, wherein creating comprises coupling each thin strut to a corresponding thick strut by a hinge joint having a plastically deformable thinned region.

31. The method as recited in claim 26, wherein creating comprises creating the plurality of bistable cells in a tubular.

32. The method as recited in claim 31, wherein applying comprises applying a force in a radially outward direction.

33. The method as recited in claim 26, further comprising coupling at least one thin strut to the at least one thick strut by a spring member.

34. The method as recited in claim 26, further comprising coupling at least one thin strut to the at least one thick strut by a horn spring member.

35. An apparatus, comprising:

an expandable member having a plurality of cells that are expandable from a closed position to an open position, the plurality of cells comprising cells of differing sizes.

36. The apparatus as recited in claim 35, wherein the expandable member comprises a tubular.

37. An apparatus, comprising:

an expandable member having a plurality of cells that are expandable from a closed position to an open position, the plurality of cells comprising cells of differing configurations.

38. The apparatus of claim 37, wherein the expandable member comprises a tubular.

39. An expandable device for use in a wellbore environment, comprising:

a plurality of expandable cells; and
a locking mechanism to hold the plurality of cells in an expanded state.

40. The expandable device as recited in claim 39, wherein the locking mechanism comprises a ratchet mechanism.

41. The expandable device as recited in claim 39, wherein the plurality of cells comprises bistable cells.

42. The expandable device as recited in claim 39, wherein each cell of the plurality of cells comprises a thick strut and a thin strut.

43. The expandable device as recited in claim 39, wherein the plurality of expandable cells are arranged in a tubular.

44. The expandable device as recited in claim 40, wherein the ratchet mechanism comprises a finger ratchet.

45. The expandable device as recited in claim 40, wherein the ratchet mechanism comprises a fork ratchet.

46. The expandable device as recited in claim 40, wherein the ratchet mechanism comprises a wedge.

47. The expandable device as recited in claim 39,

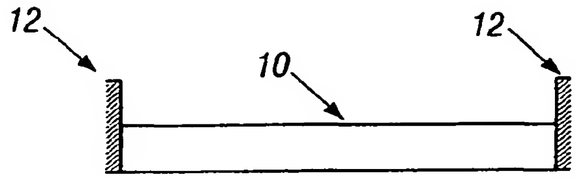

FIG. 1A

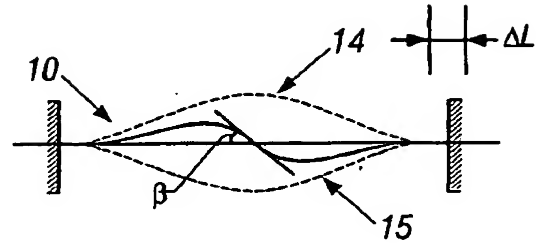

FIG. 1B

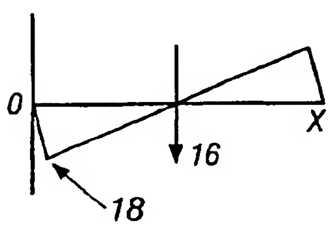

FIG. 2A

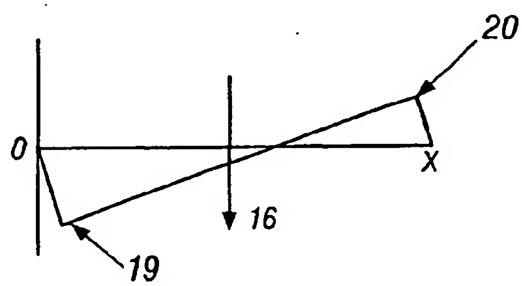

FIG. 2B

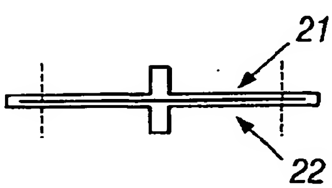

FIG. 3A

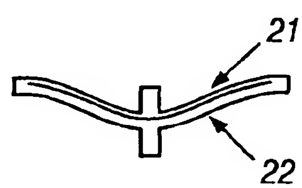

FIG. 3B

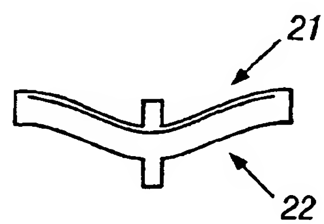

FIG. 3C

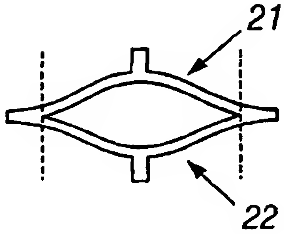

FIG. 3D

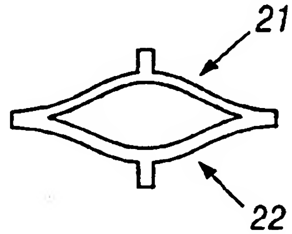

FIG. 3E

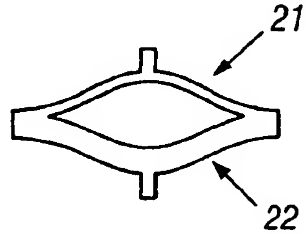

FIG. 3F

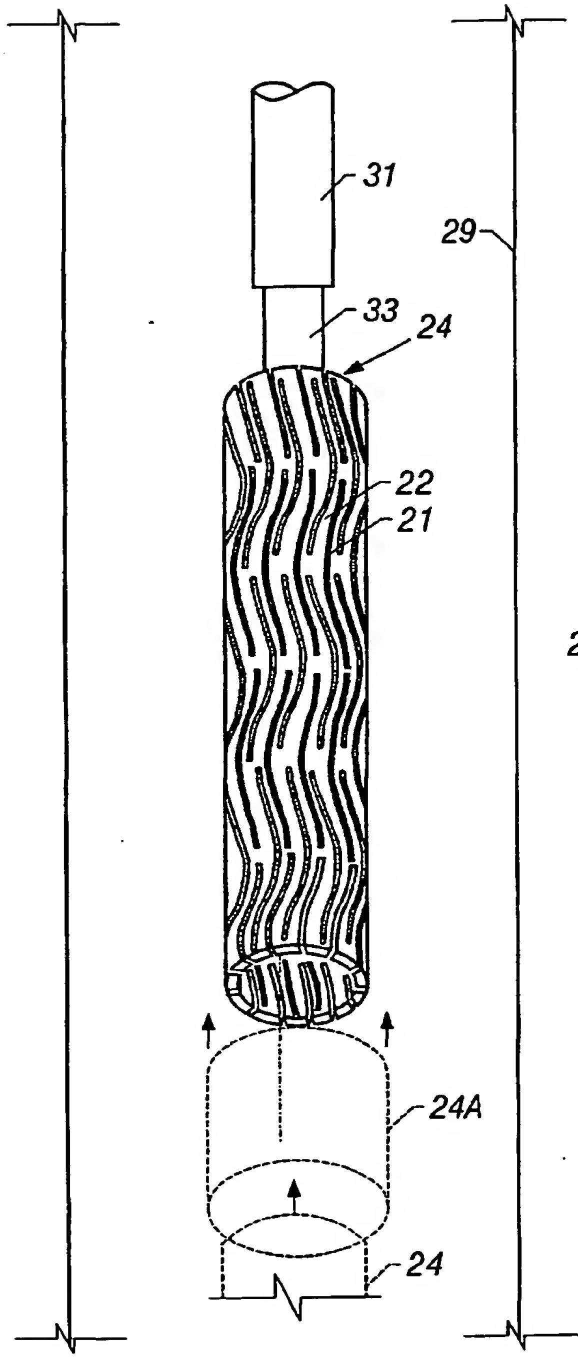

FIG. 4C

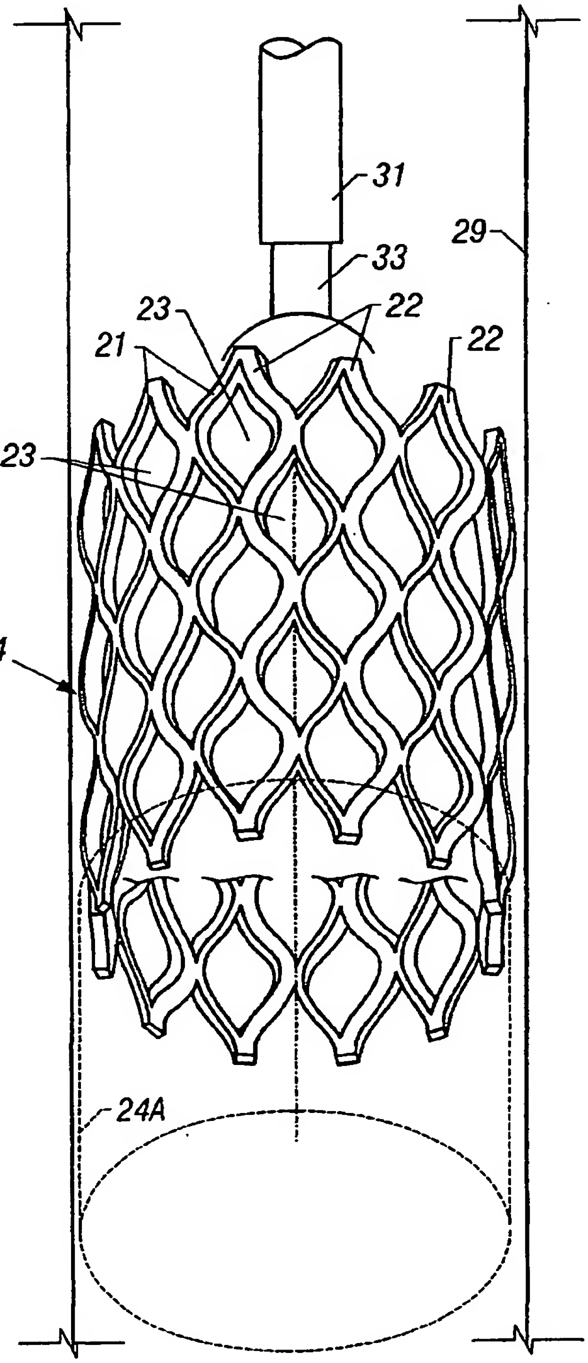

FIG. 4D

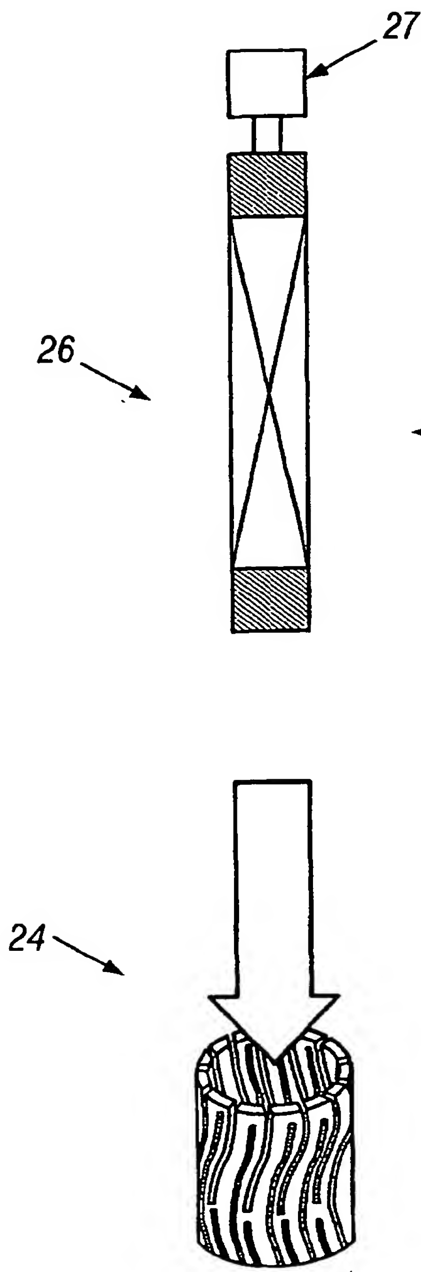

FIG. 6A

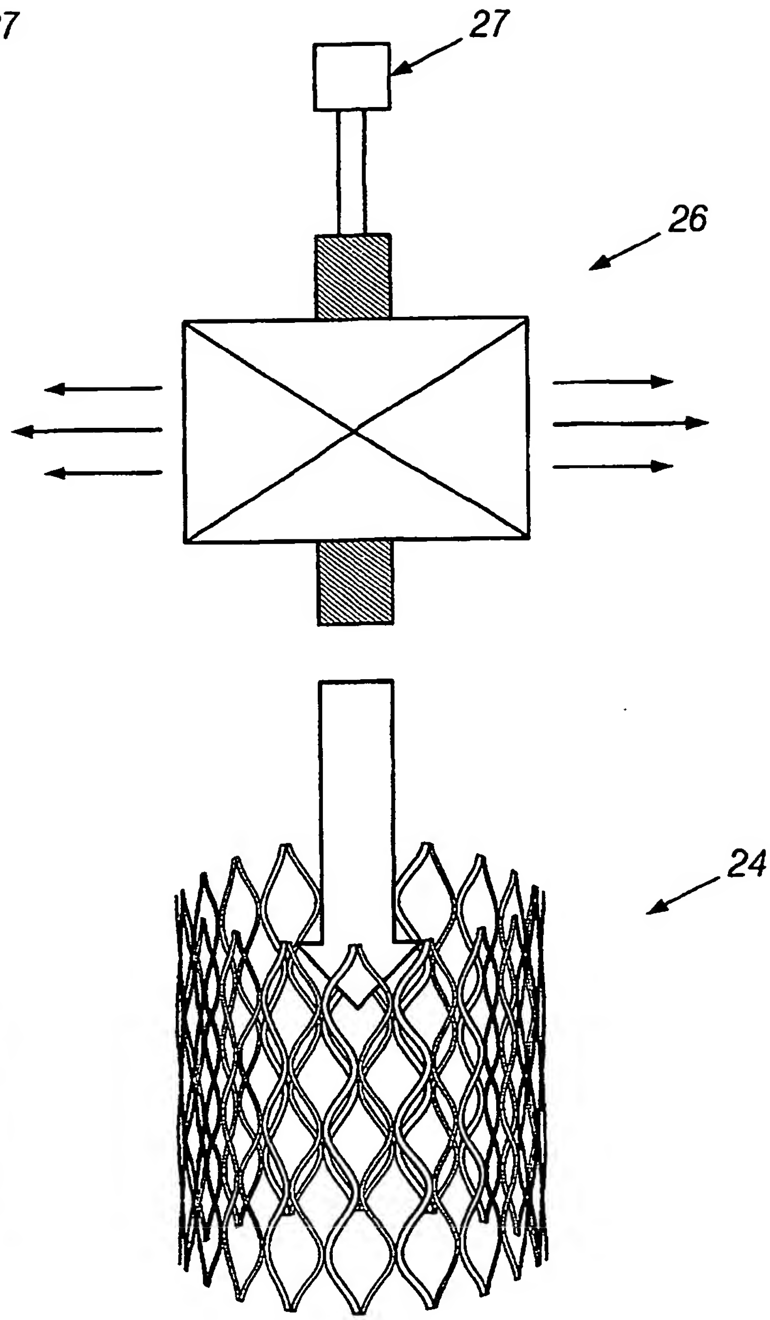

FIG. 6B

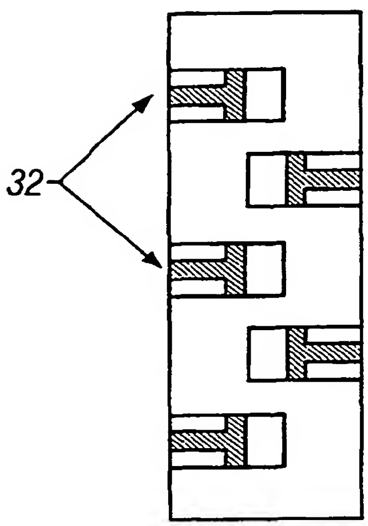

FIG. 8A

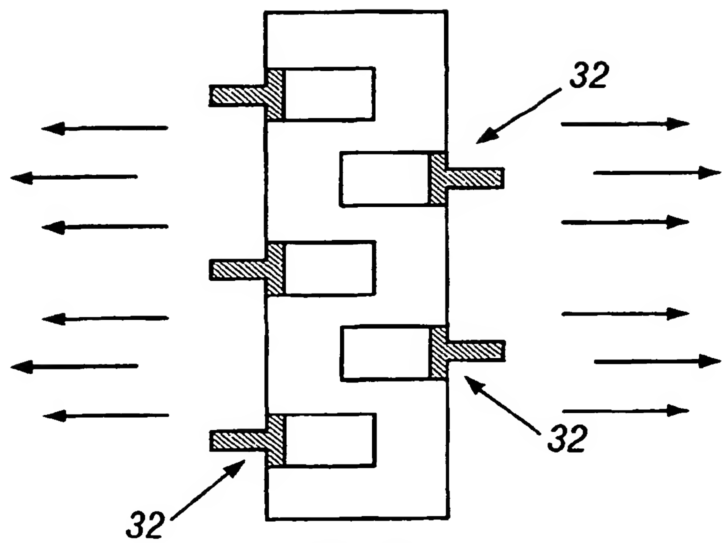

FIG. 8B

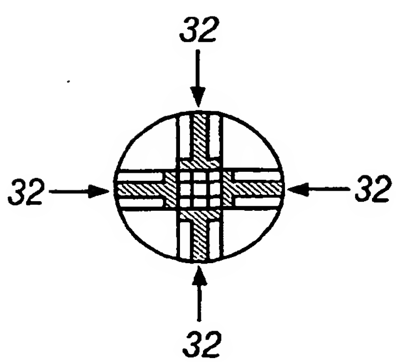

FIG. 8C

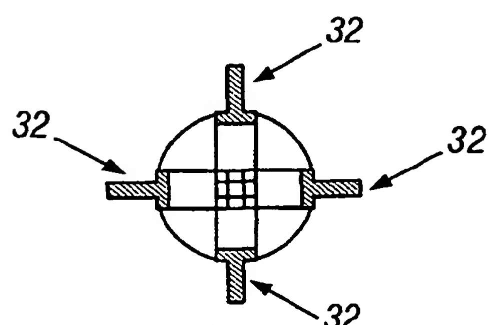

FIG. 8D

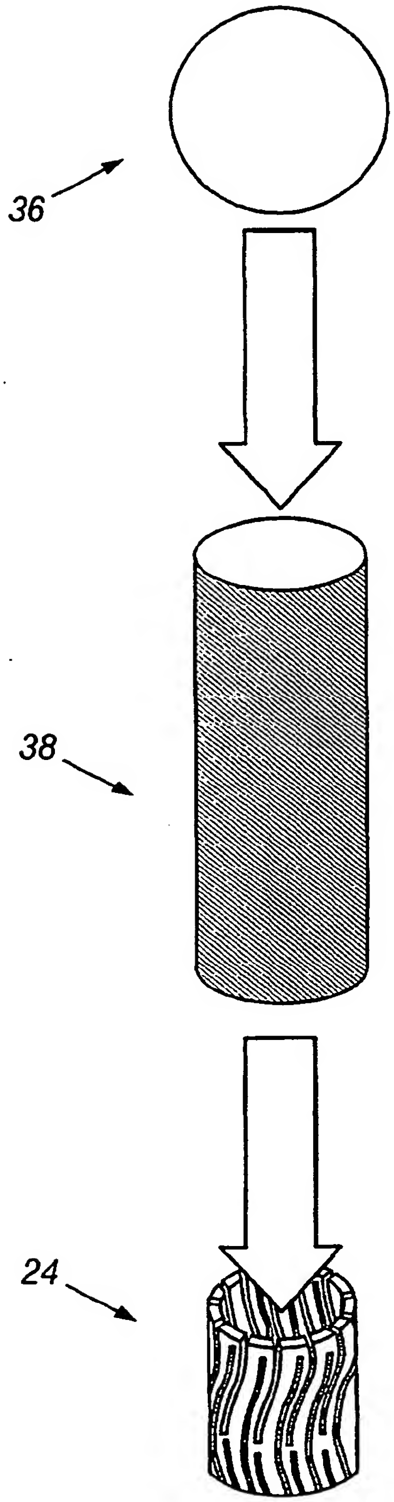

FIG. 10A

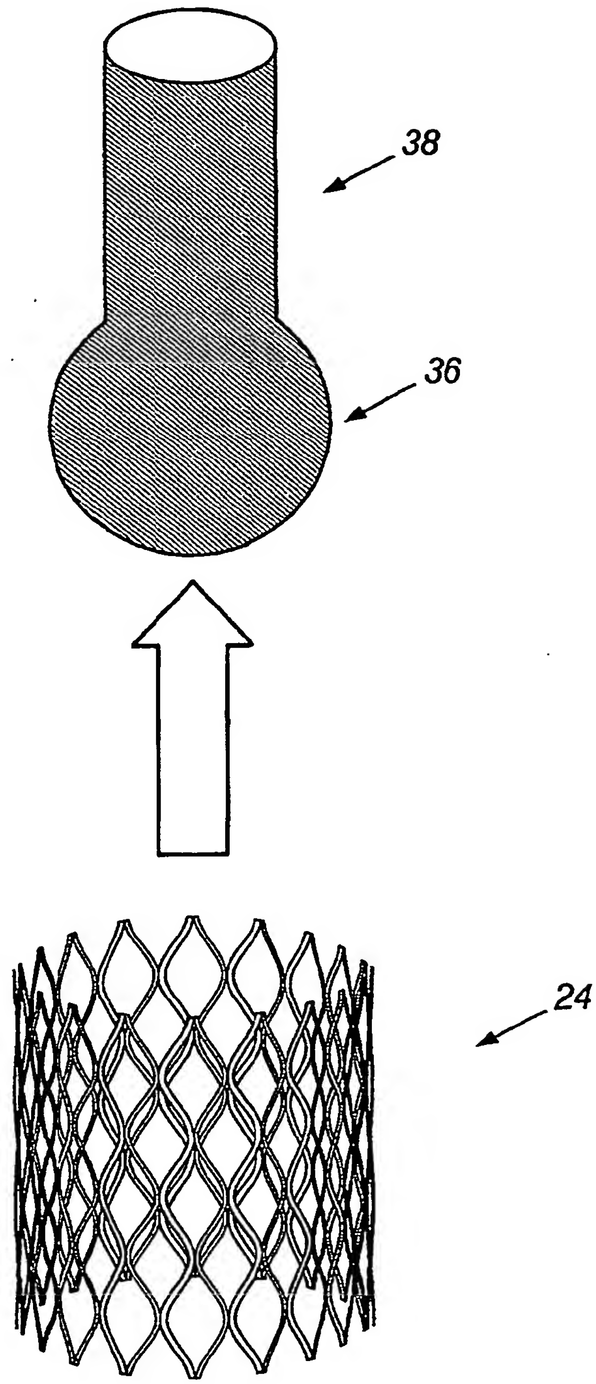

FIG. 10B

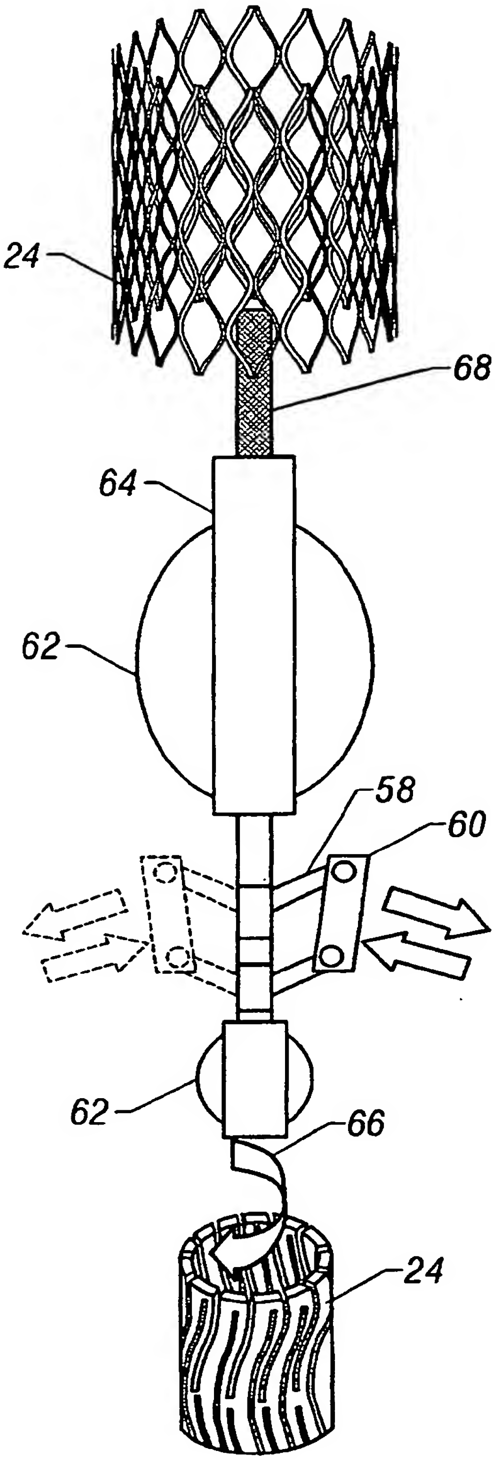

FIG. 12

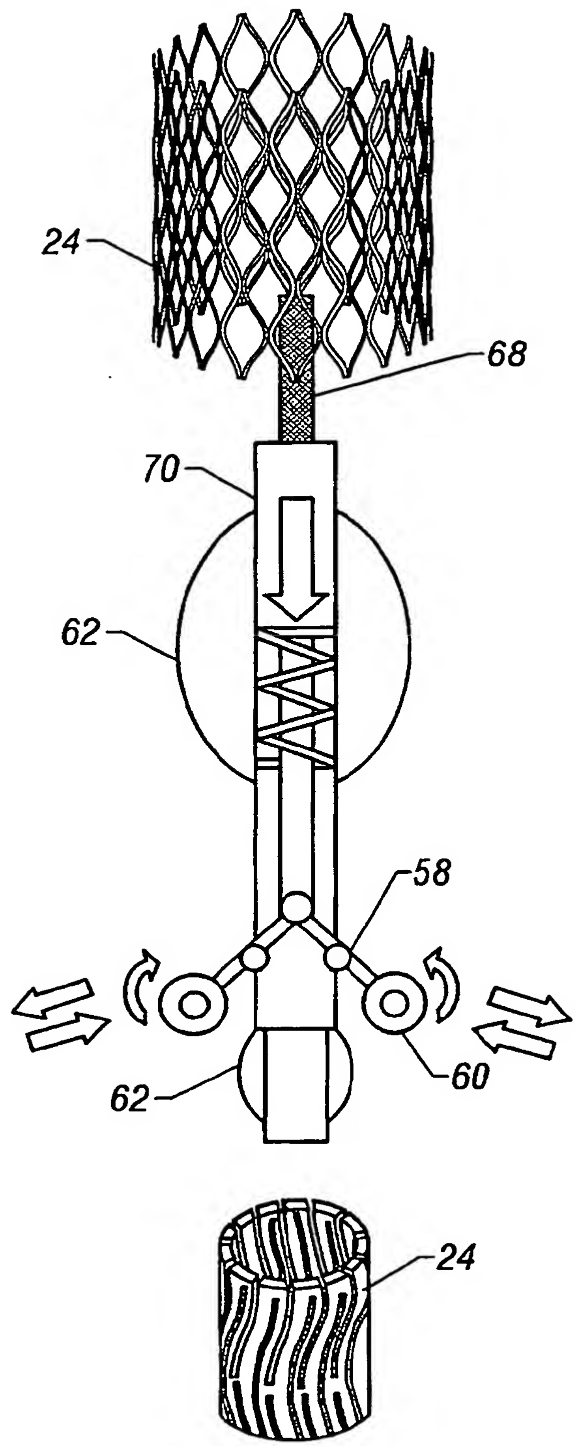

FIG. 13

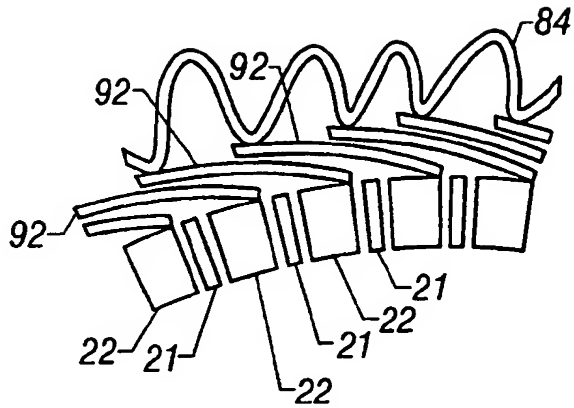

FIG. 18A

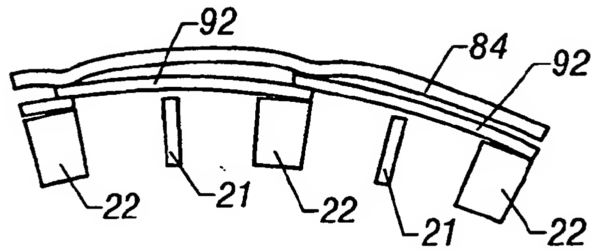

FIG. 18B

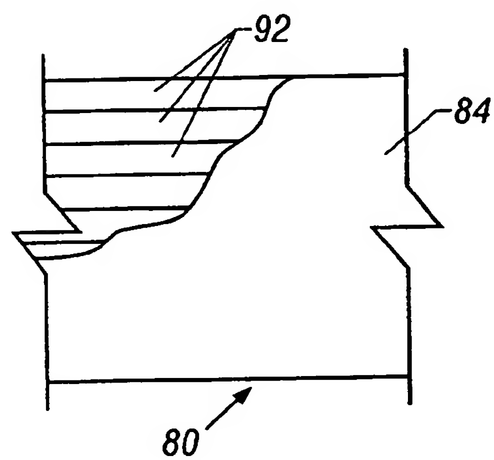

FIG. 18C

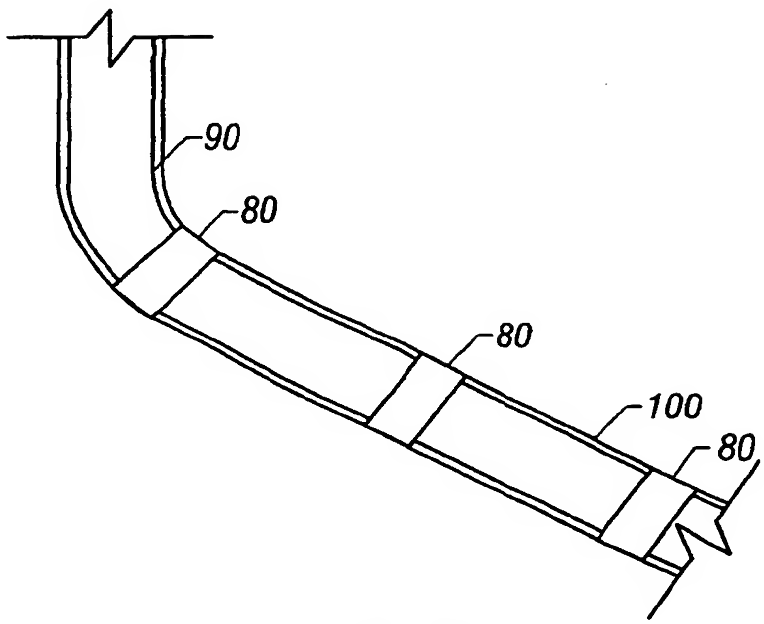

FIG. 20

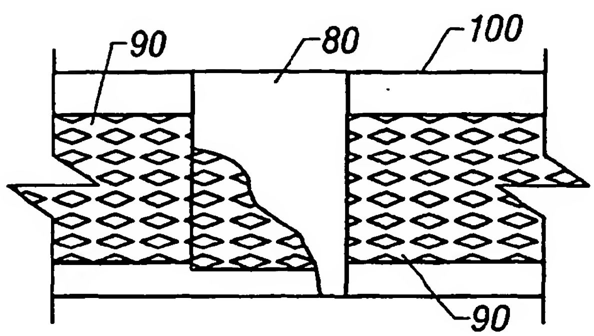

FIG. 21

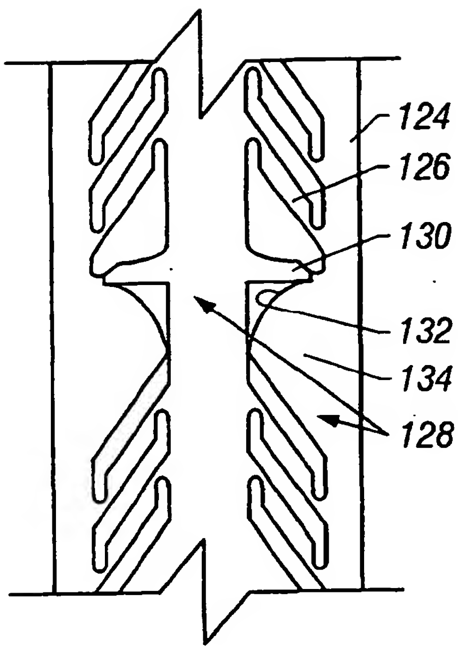

FIG. 23A

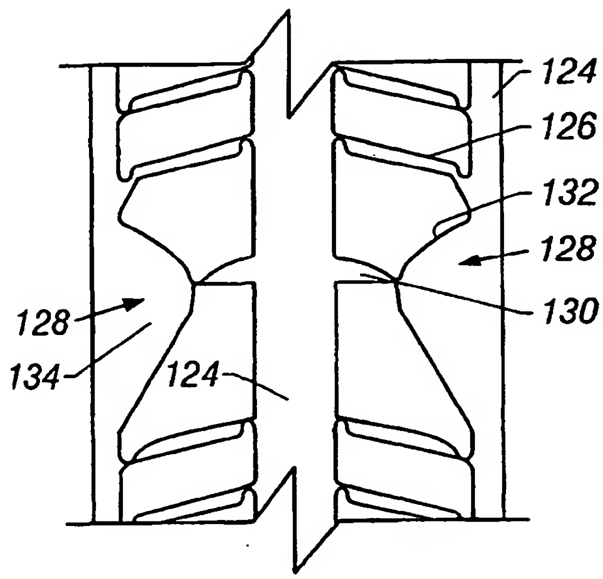

FIG. 23B

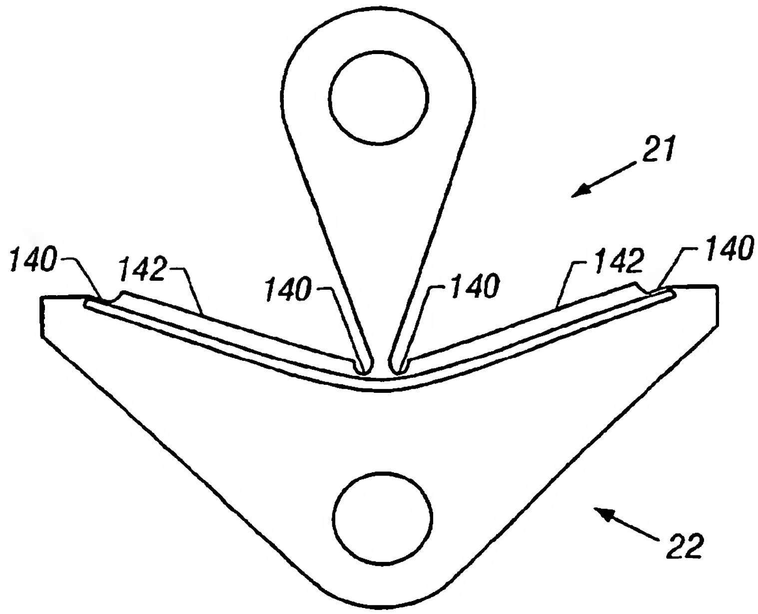

FIG. 25A

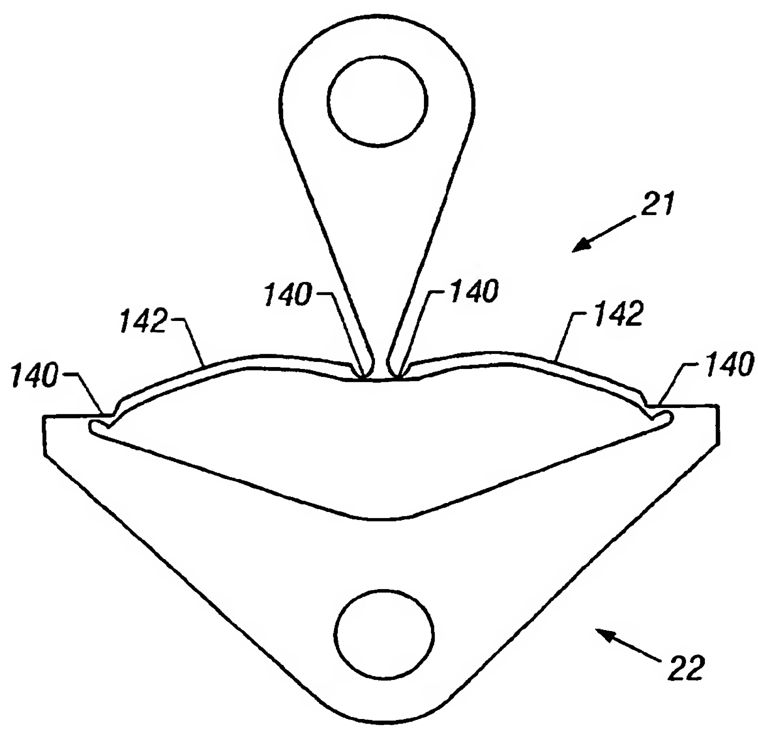

FIG. 25B

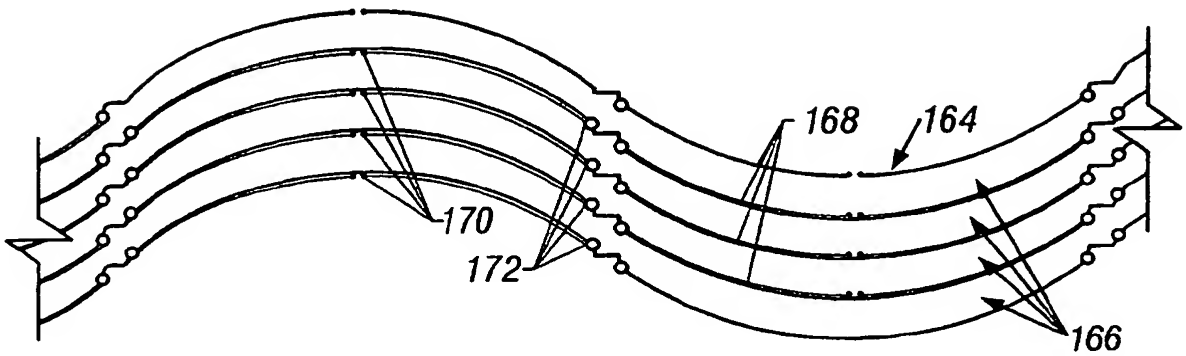

FIG. 27A

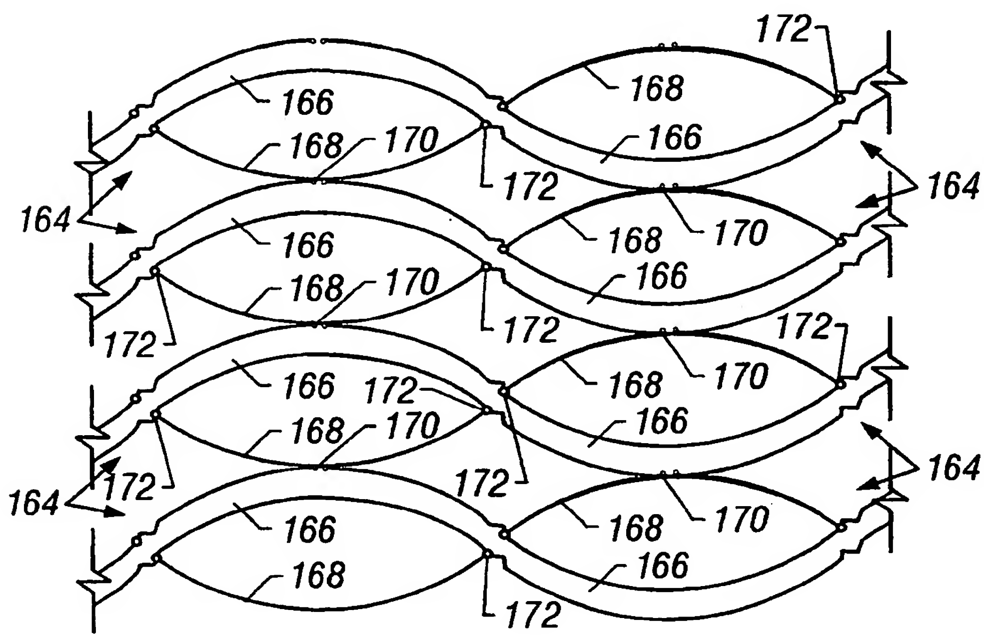

FIG. 27B

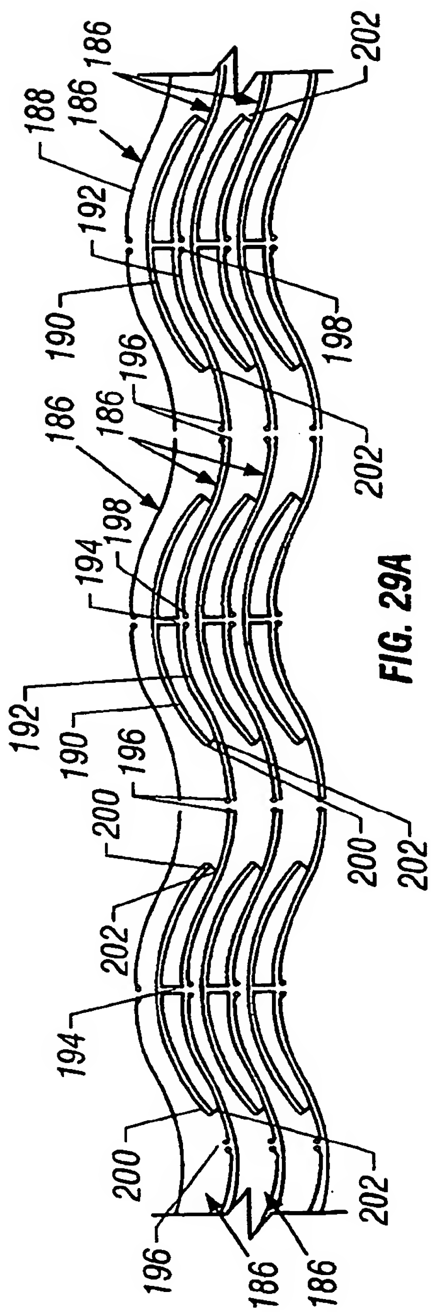

FIG. 29A

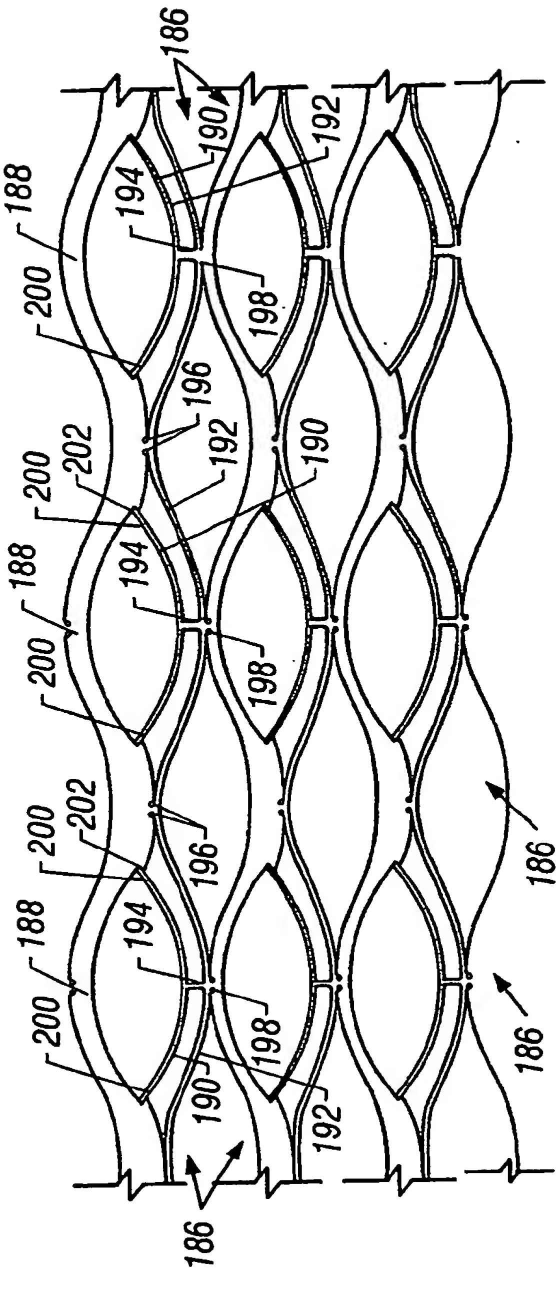

FIG. 29B

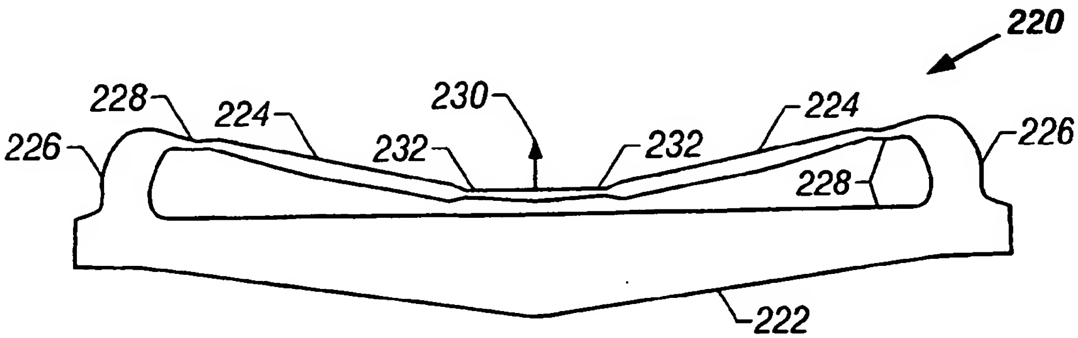

FIG. 31A

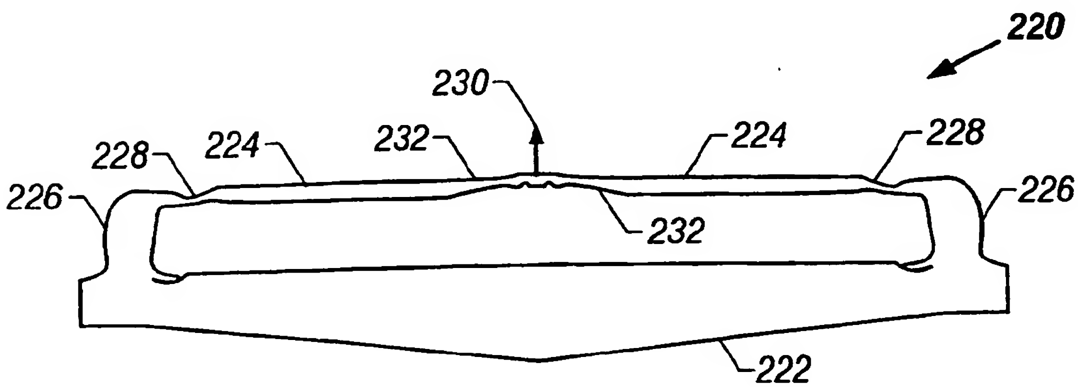

FIG. 31B

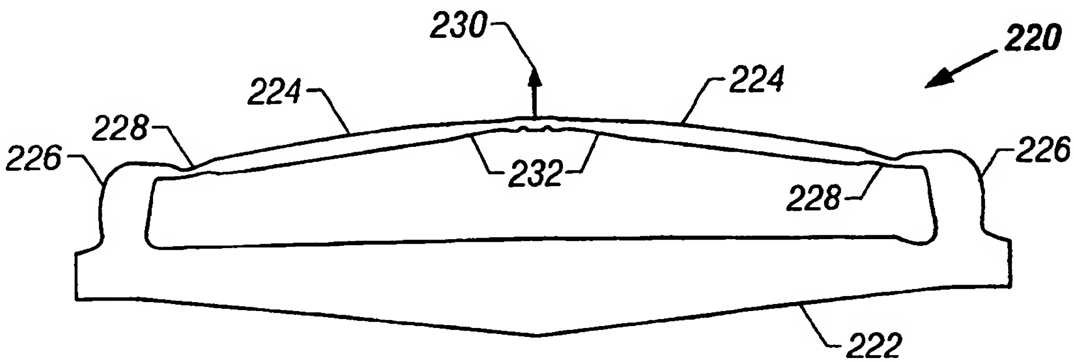

FIG. 31C

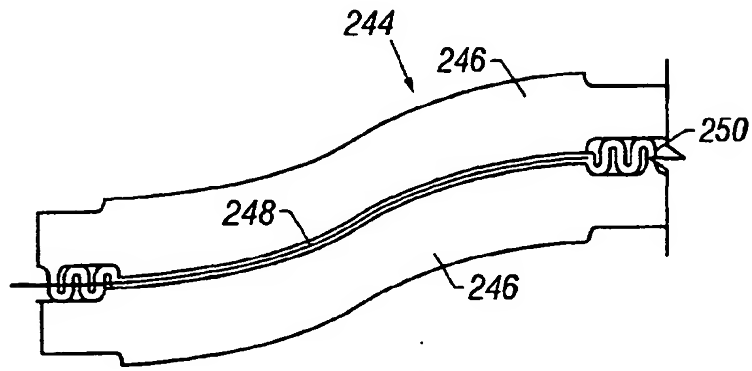

FIG. 33

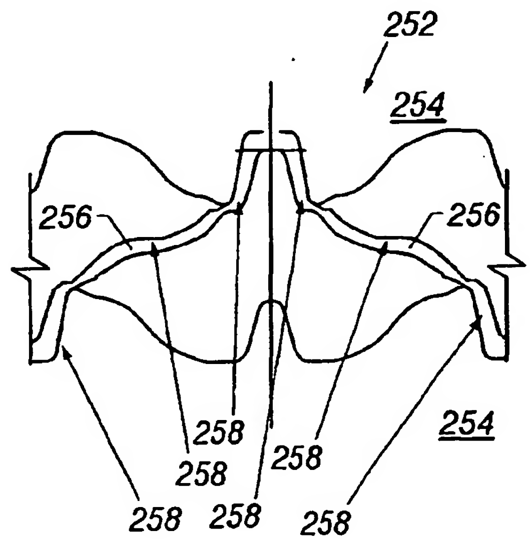

FIG. 34

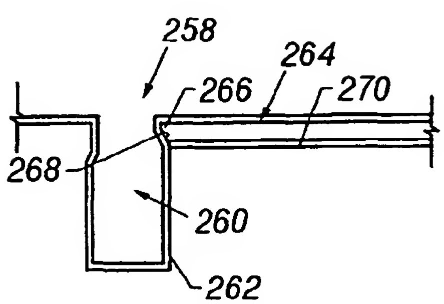

FIG. 35A

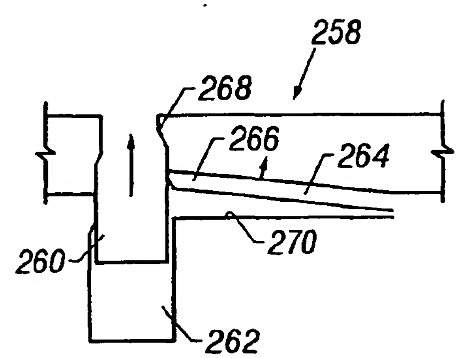

FIG. 35B

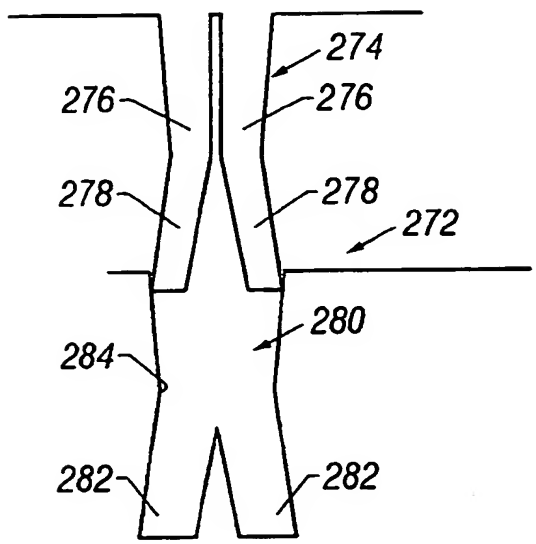

FIG. 36C

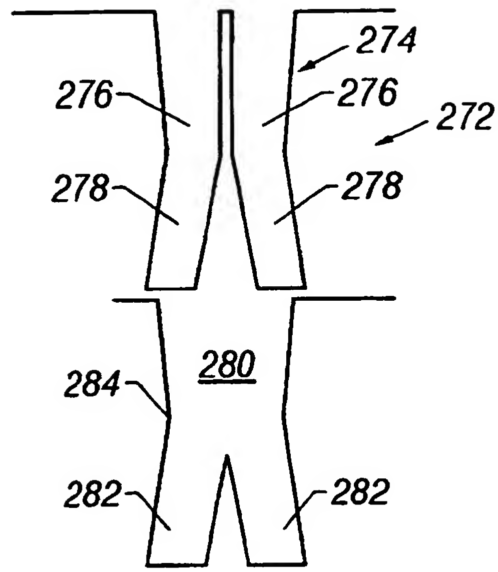

FIG. 36D

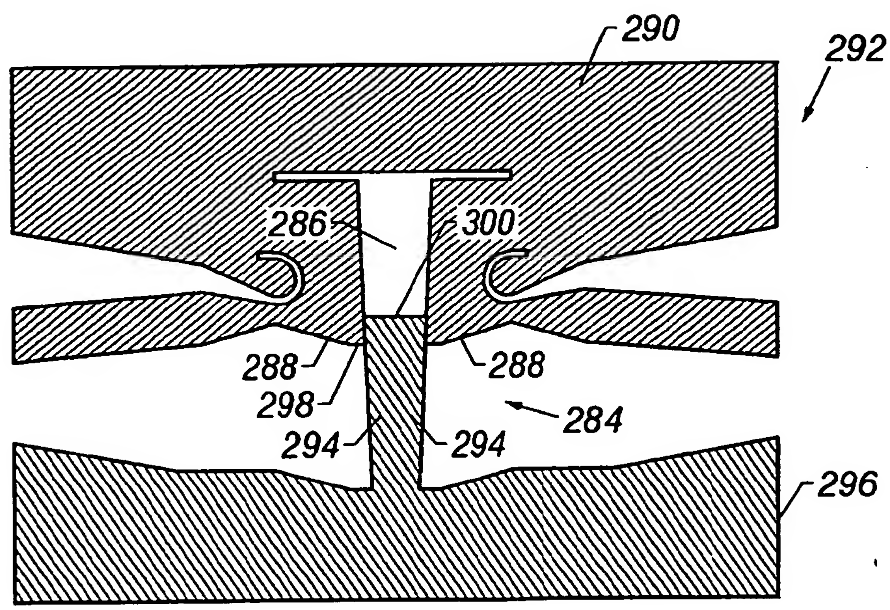

FIG. 37

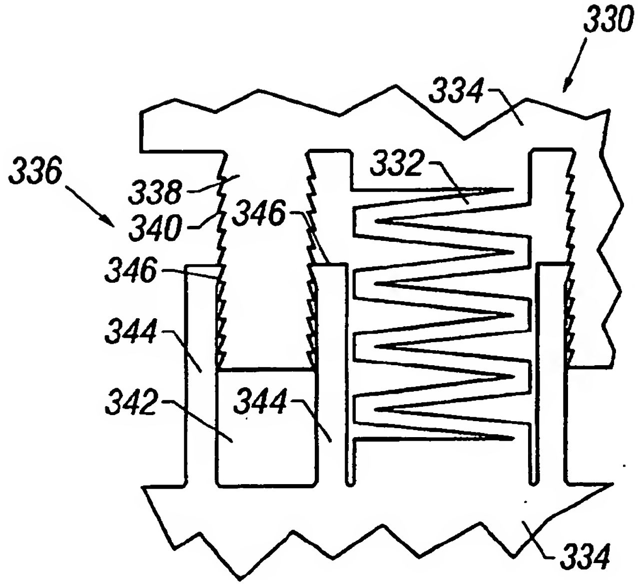

FIG. 40A

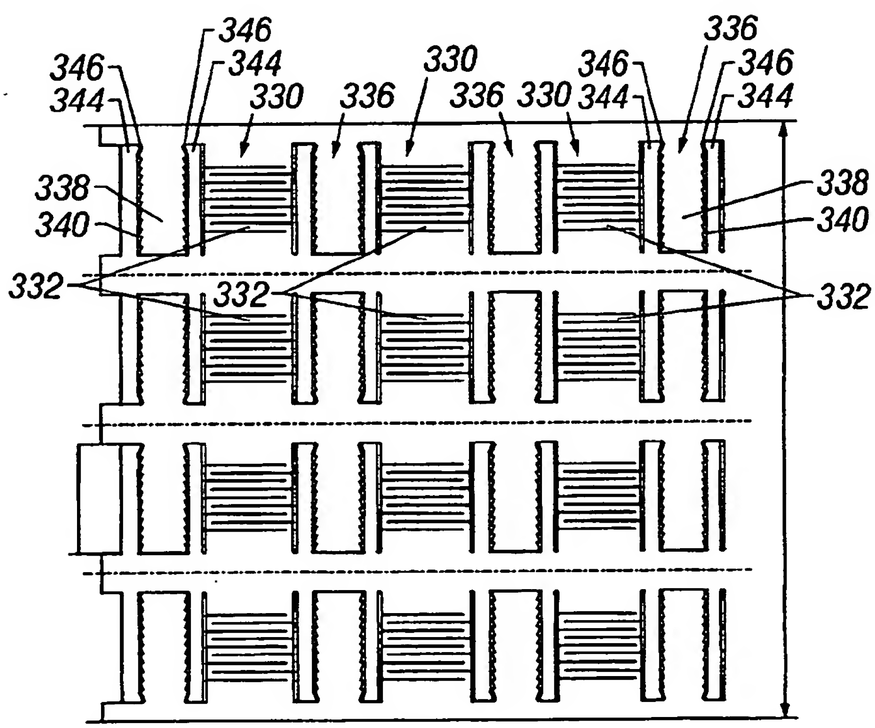

FIG. 40B

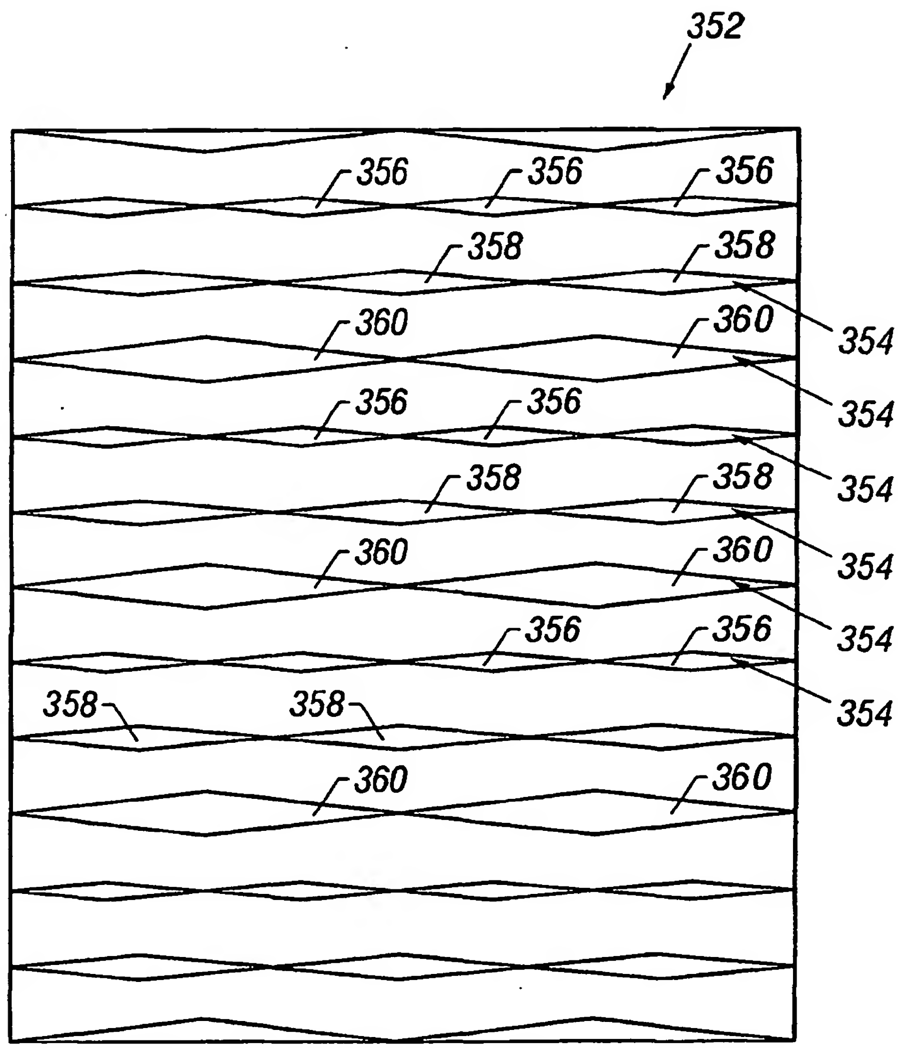
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FIG. 42